

Application of System Operational Effectiveness to Launch Vehicle Development and Operations

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Abstract – The Department of Defense (DoD) defined System Operational Effectiveness (SOE) model provides an exceptional framework for an affordable approach to the development and operation of space launch vehicles and their supporting infrastructure. The SOE model provides a focal point from which to direct and measure technical effectiveness and process efficiencies of space launch vehicles. The application of the SOE model to a space launch vehicle's development and operation effort leads to very specific approaches and measures that require consideration during the design phase. This paper provides a mapping of the SOE model to the development of space launch vehicles for human exploration by addressing the SOE model key points of measurement including System Performance, System Availability, Technical Effectiveness, Process Efficiency, System Effectiveness, Life Cycle Cost, and Affordable Operational Effectiveness. In addition, the application of the SOE model to the launch vehicle development process is defined providing the unique aspects of space launch vehicle production and operations in lieu of the traditional broader SOE context that examines large quantities of fielded systems. The tailoring and application of the SOE model to space launch vehicles provides some key insights into the operational design drivers, capability phasing, and operational support systems.

1. System Operational Effectiveness (SOE) Framework

The System Operational Effectiveness (SOE) framework was established to guide the early program system engineering in the consideration of the system's operational uses and support requirements. The early identification of these requirements provides for a more effective system in availability, support processes, and cost in accomplishing the overall mission objectives. The application of these principals in early launch vehicle definition activities is essential to providing cost effective access to space for a variety of missions and mission destinations.

The SOE process flow is illustrated in Figure 1. Understanding the context of the launch vehicle operations and uses is an essential first step. This understanding should be captured in the Concept of Operations. This understanding includes the capabilities required to achieve the missions set, customers to be served, manufacturing concepts, launch site processing, launch and ascent flight operations, supportability, and sustaining engineering. Once this understanding is established, then the major functions necessary for the launch vehicle and the associated design requirements can be defined with the supportability capabilities properly accounted. Flowing out of the design, the failure assessments become available from which to identify the probable failure conditions. This knowledge provides the basis for planning the Integrated Logistics Support (ILS) to provide timely, cost effective resolution to failures during manufacturing, transportation, assembly, integration, test, and launch operations. The ILS includes the

identification of appropriate line replaceable units (LRU) and definition of spares policy. The support policies can be evaluated during various system tests, but most effectively are demonstrated during the flight testing of the launch vehicle. These flight tests provide a full scale evaluation of the support capabilities while providing beneficial support functions to the flight test. As the launch vehicle progresses through the life cycle phases, the application of the SOE model has different emphasis points.

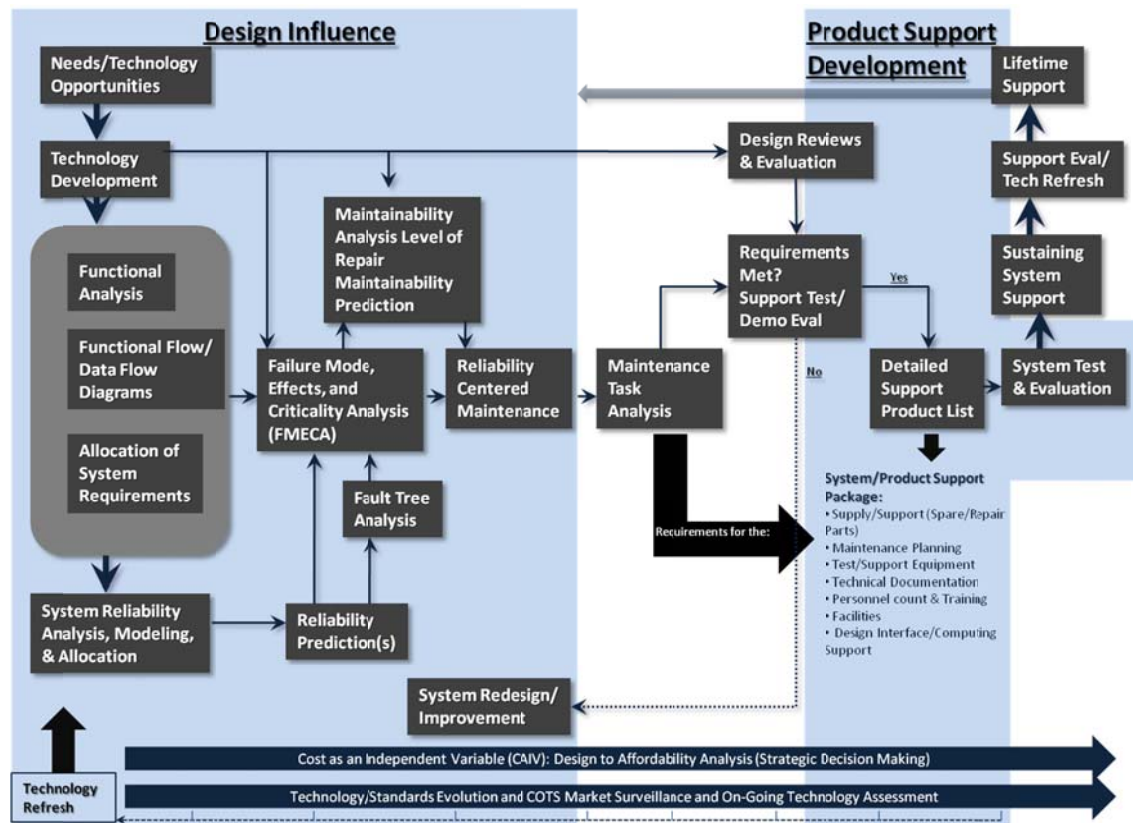


Figure 1: Application of the SOE Model in the Launch Vehicle Life Cycle

Understanding the mission context and launch vehicle concept relationship is essential to defining a sustainable program over the life cycle of the launch vehicle. For a launch vehicle, the mission context is not a single mission. Rather the mission context is described as a launch capability supporting many mission types. Mission types are many and broadly can be defined as crewed, low earth orbit (LEO) cargo, and beyond earth orbit (BEO) cargo. Each of these mission types brings a unique set of lift mass, certification, and payload/crew capsule services requirements. Deriving directly from these mission types, a launch vehicle concept may be defined considering both performance (mass to orbit, flight services) and sustainability (start of manufacture through post flight analysis and feedback for each mission). It is essential to have the correct viewpoint when looking at the launch vehicle concept. From a single mission viewpoint, performance is a key gate which must be achieved for the mission to be successful. From a long term program viability view point, sustainability is crucial for the launch vehicle to be affordable to customers and stakeholders. These viewpoints must both be met in the definition and development of a launch vehicle program.

The key construct supported through the SOE framework is to design the launch vehicle for supportability and then to support the launch vehicle design during operations. The original SOE model considered systems that were deployed in mass such as land vehicles, aircraft, etc. These systems operate in many

different areas and environments and deployed by units. Launch vehicles are generally manufactured as needed and deployed individually. Deployment is typically to a single site although there are vehicles that have one or two additional launch sites that may support their vehicles. This leads to some different philosophies on design for support and supporting the design as illustrated in Figure 2. During definition and design, the launch vehicle supportability concept must be defined and understood to provide guidance on the launch vehicle design.

Design for support of a launch vehicle can be defined into several categories: Integrated Logistics Support (ILS), Supportability Requirements, Flight and Launch Operations Definition, and Total Ownership Cost (TOC)/Life Cycle Cost (LCC). Supportability requirements are the key aspect in driving the launch vehicle design to a supportable and cost effective system. The requirements address not only the system characteristics (launch availability, reliability, maintainability, producibility, human factors, accessibility, transportability, etc.). ILS planning considers how the launch vehicle will be maintained, supply chain management (SCM), sparing philosophy, transportation, ground support equipment, personnel training and certification. Flight and Launch Operations provide the definition of the operational control centers and the operations team to support both launch and flight operations. TOC (often referred to as LCC) provides key evidence of the impact of design decisions on the Production and Operations (P&O) costs. The TOC allows the design to be driven to a more cost efficient design during the P&O phase.

Support the Design of a launch vehicle can be defined into the following categories: Sustaining Engineering, Execute ILS, Launch Availability Maintenance, Incorporate Block Upgrades, Provide Customer Support, Affordability Analysis, and Manage Safety. Sustaining engineering encompasses production engineering, post flight analysis, configuration item nonconformance/discrepancy dispositions, obsolescence mitigation, and technology refresh needs. Block upgrades are incorporated into the launch vehicle as needed through the program. During P&O the ILS planning as defined above, is executed. Launch availability is maintained to ensure the vehicle maintain their availability over the life of the program. As block upgrades, technology refresh, and obsolescence are implemented, launch availability can improve or degrade of the life of the program. Customer support is a key activity to assist customers understanding of vehicle capabilities and environments in order to ensure the payloads fit within these. Affordability analysis provides updates to the TOC to ensure vehicle Production and Operations cost are managed within the desired envelop. Safety is a critical aspect to be managed for ground crew operations and, where applicable, flight crew.

The design for support features are directly coupled to the support the design characteristics. This coupling requires that the basic philosophies and approaches be established in support of the design requirements early in the design phase (Phase A). These requirements guide the design of the launch vehicle, the design then drives out the specific operational procedures and methods needed to support the launch vehicle during P&O. If this coupling is not in place, then the design of the vehicle will not be compatible with the program plans for support resulting in a support plan driven by other factors in vehicle design such as mass efficiency, development cost minimization, etc. These other design factors lead to expensive and time consuming support approaches if not balanced with a clear definition of the support concept guiding the design.

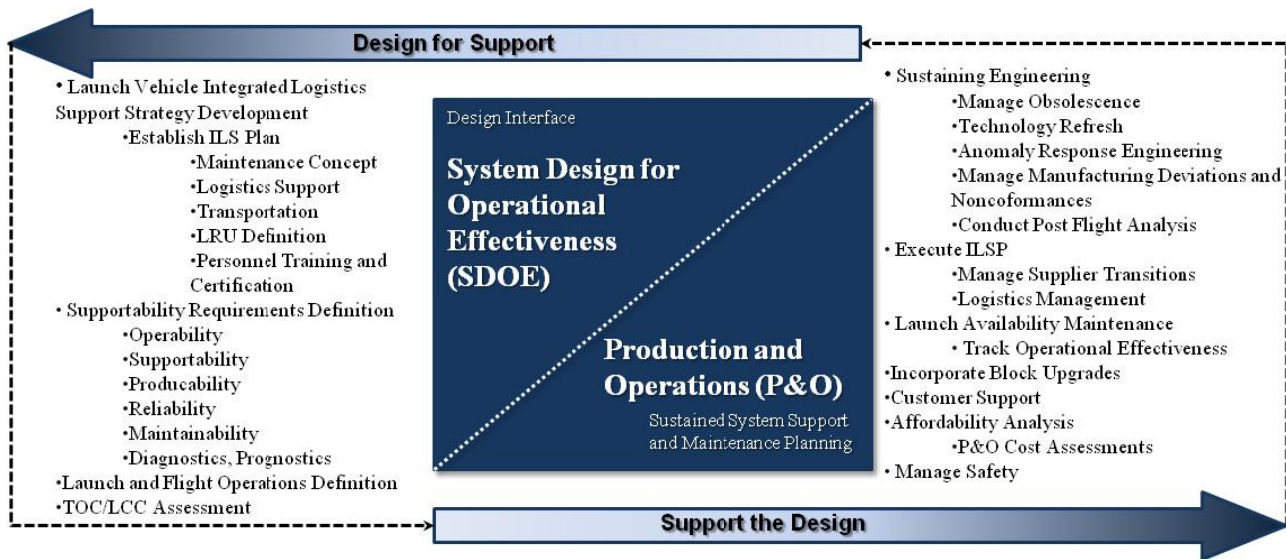


Figure 2: Design for Support/Support the Design Construct

Balancing launch vehicle mission performance and support requirements requires an understanding of the interrelationships of the requirements as illustrated in Figure 3. For systems such as vehicle or aircraft, a system availability model works well in describing the relationship in executing the mission and supporting the mission. These systems spend of their life cycle in the field after manufacturing. For a launch vehicle, the mission execution time is roughly 10 minutes. The assembly time, including any storage time, for a launch vehicle constitutes the bulk of its life. Consequently most support effort is applied during the assembly of the vehicle and the launch operations. Failures in flight are not repairable unless specific design features are included (i.e., redundancy, predefined failure states) and so do not affect mission availability, only mission reliability. For failures occurring prior to launch, the support and maintenance actions are executed to return the launch vehicle to operation. Following this, maintenance actions such as design modifications, may take place to ensure future vehicles (i.e., the fleet consisting of all vehicle manufactured over the life of the program) do not encounter the same issues. These maintenance actions can be brought about from both prelaunch anomalies and flight anomalies.

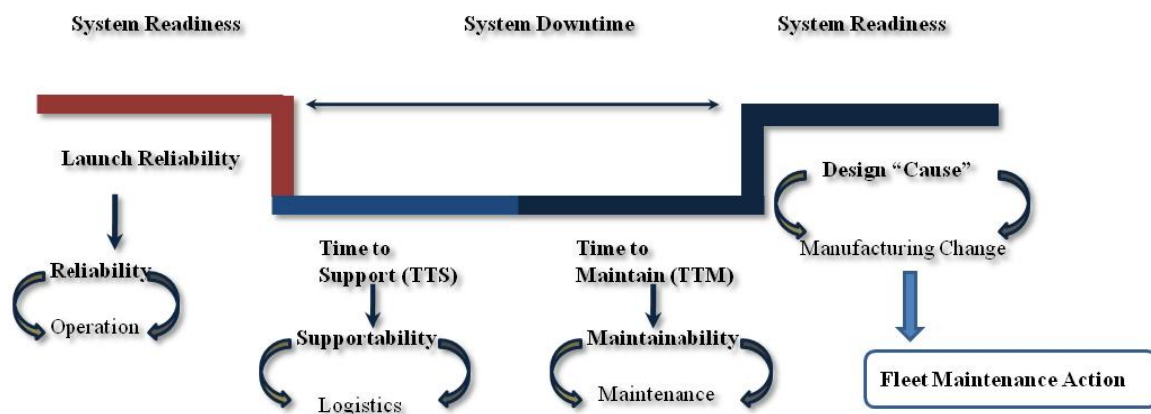


Figure 3: Coupling Between Mission Performance and Mission Support

2. System Operational Effectiveness (SOE) Model Application

The SOE model provides an excellent structure to address the support characteristics during development and then to manage these characteristics during Production and Operations (P&O). Figure 4 illustrates the basic model structure. The model has 4 major characteristics groupings for Technical Performance, System Availability, Process Efficiency, and TOC. These basic characteristics are combined to produce Design Effectiveness, Mission Effectiveness, and Affordable Operational Effectiveness. These characteristics, when properly balanced lead to a system which meets both mission performance objectives and program support objectives.

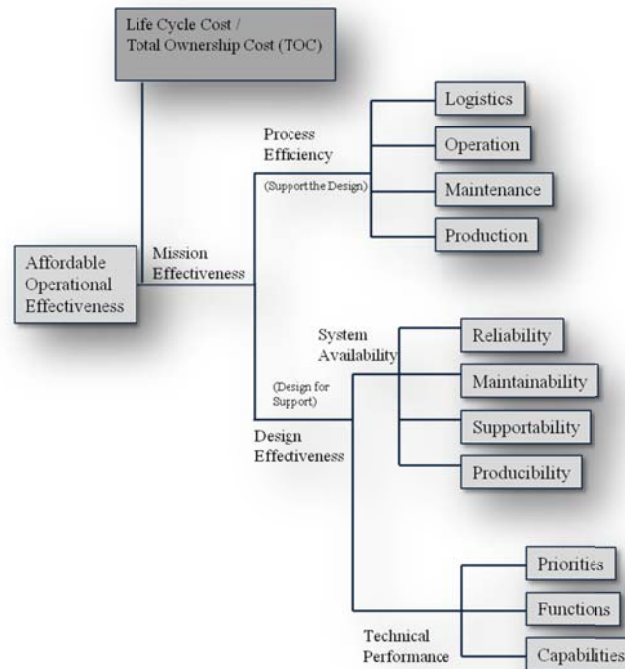


Figure 4: System Operational Effectiveness (SOE) Diagram

Designing for optimal Operational Effectiveness with the SOE model requires a balance between System Effectiveness and System Life Cycle Cost (LCC)/TOC. The focus isn't strictly on System Availability or System Performance of the space launch vehicle(s) (Design for Support), but includes multiple engineering aspects that account for the cost-effective responsiveness and relevance of the support system and infrastructure (Support the Design). Process Efficiency and its corresponding branches are the "Support the Design".

The SOE approach is used to explain the dependency and interplay between the Technical Performance, System Availability, Process Efficiency, and the Life Cycle Cost. This overarching perspective provides a context for the "trade space" available to a project manager along with the articulation of the overall objective of maximizing the System Operational Effectiveness. The SOE model requires proactive analysis inputs from corresponding disciplines for a trade or suggested change which are then assigned a quantifiable metric or value. Along with the metric, each input is given a weighting factor that proportions emphasis on certain characteristics and attributes (Design Effectiveness, System Availability, Process Efficiency). The characteristics/attributes are provided a rank and the average amongst the ranks for a trade/suggested change results in the Mission Effectiveness.

The SOE model refers to Key Performance Parameters (KPPs) as measurements of System Operational Effectiveness (SOE). Within NASA KPPs are used in various ways. Technology programs use KPPs to define acceptable and measureable System Capabilities for technology development activities. In this context KPPs are the required technical performance a technology development must demonstrate in order to advance to the development phase (Phases C, D). In the development phases, KPPs are represented as Measures of Effectiveness (MOE) and Measures of Performance (MOP). These MOEs and MOPs provide guidance to Agency management on how well the Program is accomplishing the requirements, including stakeholder expectations, of the launch vehicle development.

Typically, a portion of the MOPs and MOEs are managed as Technical Performance Measures (TPMs). For a launch vehicle these have traditionally consisted of several categories including Mass, Propulsion Performance, Flight Control, Avionics. In some programs, TPMs such as Production Cost have also been used to guide developments. These are tied back to stakeholder expectations to ensure the long term economic viability (affordability) of the launch vehicle. Often financial metrics are reported separately through tools such as Earned Value Measurement (EVM). These EVM metrics are another form of KPPs and fit well within the overall SOE framework. Considering all these forms of KPPs, the SOE model properly integrates all of these and provides an excellent framework in which technical and operational progress can be properly understood as an interrelated set of measures.

2.1. Design Effectiveness

Design Effectiveness includes Technical Performance and System Availability as indicated in Figure 5.

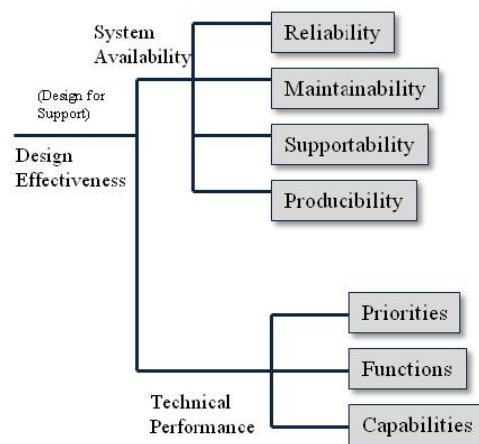


Figure 5: Design for Support/Design Effectiveness portion of the SOE Diagram

2.1.1. Technical Performance

For a launch vehicle specific TPMs can be identified which characterize the Technical Performance. Table 1 lists these metrics, organized by categories and grouped by functions and capabilities. Capabilities are defined as performance attributes including mass to orbit, delta v, gross lift off weight, orbit insertion accuracy. System functions are the mission capabilities and scenarios the launch vehicle serves. These include various mission the various mission types such as crewed, payload, and combined missions. Payload can further be broken into planetary science missions, earth orbiting missions, large space structures, etc. These functions are essential in understanding the proper use context of the launch vehicle. The SOE model also includes Priorities as Technical Performance characteristics. Priorities can be taken in many ways but are related to importance assigned to accomplishing specific mission objectives. In this sense, Priorities represent the relative weightings of the capabilities provided as applied to different mission types. These three factors are linked and be measuring the integrated set of factors, the System Performance of the launch vehicle can be determined.

Categories	Technical Performance Metric	Type
Mass		
	Mass to Orbit	Capability
	Dry Mass	Capability
Propulsion Performance		
	Specific Impulse	Capability
	Thrust	Capability
	Flight Performance Reserve (FPR)	Capability
Clearance		
	Lift Off	Function
	Separation	Function
Flight Performance		
	Stability	Function
	Maximum Dynamic Pressure	Function
	Load Indication	Function
	Delta V	Capability
	Orbital Insertion Accuracy	Capability
Avionics Performance		
	Data Bus Bandwidth	Capability
	Data Processor Throughput	Capability
	Memory Usage	Capability
	Communication Bandwidth	Capability

Table 1: Technical Performance Measures

2.1.2. System Availability

The SOE model for System Availability is composed of Reliability, Maintainability, Supportability, and Producibility. These branches for System Availability are quality characteristics and important task because they may constrain the overall design solution(s) and architecture as well as impact the set of derived and derived technical requirements. These system characteristics can be categorized as Mission Readiness (leading up to launch) and Flight Performance. Specific measures of these characteristics are listed in Table 2.

Categories	Technical Performance Metric	Type
Mission Readiness		
	Producibility	Producibility
	System Readiness	Supportability
	Launch Availability	Supportability
	Launch Reliability	Reliability
	Maintainability	Maintainability
Flight Performance		
	Mission Success or Loss (LOM)	Reliability

Table 2: System Availability

System Availability provides a measure of the System Characteristics of the launch vehicle. These System Characteristics describe the operation and performance of the vehicle as a whole. They indicate

how effective the overall system performs in light of the System Performance capabilities, functions, and priorities. From a launch vehicle perspective, Systems Availability addresses System Readiness and Launch Availability. System Readiness focuses on the aspects of production, assembly, and support to build and prepare the launch vehicle for the first launch attempt. This includes consideration of launch rate and production capacity to meet the launch rate. Launch Availability is focused on the ability for the vehicle to clear the pad within the required launch window set. This is not just a single launch window but takes into account the series of allowed launch windows, one of which the vehicle must launch. Launch Availability also considers maintenance downtime to return the vehicle to launch ready status after a system failure or anomaly.

The quality characteristics and attributes (such as availability etc...) impact the end product design solution and can also impact the end product performance requirements. These characteristics also influence the requirements for enabling products and life cycle services such as fabrication, assembly and integration, repair and maintenance, and testing. If there is a conflict between cost, schedule, risk, or performance and operational requirements, a trade analyses needs to be performed. The results and corresponding decisions could affect block upgrades from the original baseline, requiring another evaluation of earlier system design processes for an optimal life cycle-balanced resolution (conducted through block upgrades).

Requirements for quality characteristics will be considered early in both the stakeholder requirements definition and architecture design processes. Adding these characteristics at a later point in time will add significant re-work costs when a mature design and end products need changed to accommodate them.

2.1.2.1. Reliability

Reliability for a launch vehicle involves both launch reliability and mission (or flight) reliability. Effective design for reliability requires an understanding of the mission and operational capabilities, mission profiles, and operational environment(s) in which the system will perform. The primary objective is to minimize the risk of failure within the defined availability, cost, schedule, weight, power, and volume constraints. Generally, reliability tradeoffs are between mission reliability and launch reliability. Mission reliability is the ability of a system to perform its required functions for the duration of a specified mission profile. Mission reliability only includes failures that lead to mission failures (i.e., inability to achieve the orbital insertion point). De-rating, defined as purposeful over-design to allow a safety margin, is one way to increase mission reliability. Implementing redundant components is another way to increase mission reliability by tolerating failures in flight. However, while flight reliability is approved by redundancy, launch reliability is degraded as all redundant components must be available on lift off in order to ensure their availability during flight. Launch reliability is the probability that the vehicle will launch as planned without system failure (ground systems or launch vehicle systems) failure. All systems planned for flight or flight failure recovery must operate properly upon lift off.

2.1.2.2. Maintainability

Maintainability is defined as the ability of a system to be repaired and restored to service when maintenance is conducted by personnel using specified skill levels and prescribed procedures and resources. The emphasis on system maintainability has the objective of reducing the time and cost to maintain the system. In other words, maintainability engineering can be described as the composite of activities, methods, and practices used to influence the system design in order to minimize necessary system maintenance requirements and associated costs for both preventive and corrective maintenance. Great maintenance procedures cannot overcome poor system and equipment maintainability design. From a design influence perspective, timely focus is required on: Physical accessibility, Performance monitoring and fault localization, Built-in test (BIT) implementation (coverage and efficiency),

Elimination of false alarms, and Failure diagnostics and system prognostics. In simple terms, the intent is to reduce the time it takes for a properly trained maintainer to isolate the failure and fix it.

Intrinsic factors in maintainability may include:

- Modularity
- Interoperability
- Diagnostics
- Prognostics
- Fail Safe
- Access

Maintenance task analysis methods and tools provide a detailed understanding of necessary requirements of logistics support to sustain required system effectiveness levels. Modularity for a launch vehicle encompasses both line replaceable unit (LRU) change out as well as exchange of major assemblies such as engines or stages. Interoperability refers to the ability of components to be compatible with standard interface protocols to facilitate rapid repair and component enhancement/upgrade through “black box” technology using common interfaces. This also includes the design of physical interfaces so that mating between components can only happen correctly. Diagnostics are applicable and effective on-board or ground based monitoring and recording devices and software (built-in tests [BITs]), that provide enhanced capability for fault detection and isolation, providing faster identification of needed spares and procedures. Prognostics are applicable and effective monitoring of various components and indicate out of range conditions, imminent failure probability, and similar proactive maintenance optimization actions. For expendable launch vehicles, prognostics help identify trends in production indicating future vehicle problems. These may be due to new parts replacements or manufacturing procedures having unintended consequences in overall processing or flight performance. In the event of a failure, systems should be designed to revert to a safe mode to avoid additional damage and secondary failures. Access refers to the designed-in structural assurance that components requiring more frequent monitoring, checkout, and maintenance can be easily accessed. This includes various human factors characteristics including clear marking of hand holds and supports within the vehicle’s outer mold line.

2.1.2.3. Supportability

Supportability is the inherent quality of a system, including design, technical support data, and maintenance procedures, to facilitate detection, isolation, and timely repair/replacement of system anomalies. Supportability includes system support factors such as diagnostics, prognostics, real-time maintenance data collection, corrosion protection and mitigation, reduced logistics footprint, and other factors that contribute to achieving the optimum environment for a stable, operational system. Within NASA, these topics are addressed in the Integrated Logistics Support Plan (ILSP). The primary objective of designing for supportability is to positively impact and reduce the requirements for the various elements of logistics support during the system operations and maintenance phase. Supportability addresses:

- System training and training devices
- System Documentation/technical data
- Supply support (including spares)
- Sustaining engineering
 - Diminishing manufacturing sources and material shortages
 - Technology maturity and refreshment
- Corrosion prevention and mitigation planning (for ground based launch systems)
- Test and support equipment, to include embedded system test and diagnostics
- Facilities Management
- Packaging, Handling, Storage, and Transportation (PHS&T)

- Labor requirements and personnel skill requirements
- Standardization (system elements and parts, test and support equipment)

2.1.2.4. Producibility

Producibility is the degree to which "design for manufacturing" concepts have been used to influence system and product design to facilitate timely, affordable, and quality manufacture, assembly, and delivery of a system to the field. Producibility is closely linked to the other elements of availability as well as costs. Items that have been designed for producibility:

- Are normally easier to maintain
- Have better accessibility features
- Have lower production and sustaining costs

Emphasis on producibility can have a direct impact on reliability, maintainability, and supportability (RMS) as well as life cycle cost.

2.2. Process Efficiency

Process Efficiency reflects the manufacturing/production efficiency, operational and maintenance efficiency as shown in Figure 6. It indicates the size of the logistics infrastructure and footprint. Achieving Process Efficiency requires early, continuous emphasis on production, maintenance and the various elements of logistic support. These include supply chain management (Logistics Delay Time) and resource demand forecasting, system training, system documentation, test and support equipment, maintenance planning, packaging and handling, transportation and warehousing, and facilities. These topics are addressed in the ILSP for a NASA launch vehicle.

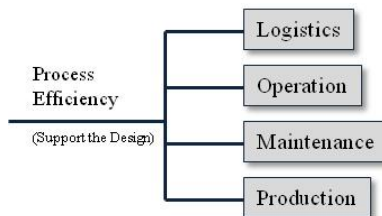


Figure 6: Process Efficiency Portion of the SOE Diagram

Process Efficiency is enhanced by:

- Application of optimization methods to reduce necessary capital investment within the system support infrastructure, e.g., spares optimization and personnel allocation optimization.
- Application of process design, re-engineering, and control to enhance efficiency of the system/product production process.
- Application of process improvement oriented technologies, e.g., asset visibility and prognostics, and multi-media technologies for documentation and training.
- Development of innovative contractual and management structures such as Performance Based Logistics (PBL).

Process Efficiency can be measured by looking at the production and assembly timelines for the launch vehicle. The optimal Process Efficiency can be defined by comparing these timelines against the available to optimally use the production and processing facilities and workforce. A system which over utilizes the facilities and workforce leads to higher costs associated with work around procedures and over time for personnel. A system which under utilizes the facilities and work force yields idle time and cost expended with no return.

2.2.1. Logistics

Logistics includes the processes put in place to support the vehicle design in assembly and operation. This is primarily focused on operations up to launch. Logistics includes the processes and policies for sparing, consumables, tools and equipment, transportation, personnel training and certification, and logistics management.

2.2.2. Operation

Operation covers both launch operations and ascent flight operations. This includes the operation control center architecture and the operational team(s) in the control centers. This also includes the operational procedures to assemble, integrate, and test the launch vehicle.

2.2.3. Maintenance

Maintenance covers the processes to maintain the vehicle during assembly, integration, storage (as appropriate), test, and launch operation. Maintenance consists of both preventative maintenance and corrective maintenance activities. Preventative Maintenance involves servicing of the vehicle to ensure fuels (e.g., hydrazine) and consumable items (e.g., battery charging, perishable items in crew capsules or payloads) are properly maintained in readiness for launch. Corrective Maintenance activities are focused on returning the vehicle to a flight ready condition due to either an anomaly or use. For expendable launch vehicles, maintenance activities end at lift off. For re-useable launch vehicles or stages (e.g., Space Shuttle Solid Rocket Boosters (SRB), Space Shuttle Orbiter, Crew Capsules), maintenance includes the activities to refurbish the vehicle or stage.

2.2.4. Production

Production involves the manufacturing site activities to build and assemble the launch vehicle stages, crew capsules, and payloads prior to assembly and integration at the launch site.

2.3. Technical Effectiveness

Technical Effectiveness is the measure of how the launch vehicle achieves both the System Performance and the System Availability measures. The launch vehicle must not only be capable of completing the mission objectives, it must also be able to repeatedly (even if with a different vehicle each launch as for expendables) achieve the objectives as required by the mission planning.

2.4. System Effectiveness

System Effectiveness considers the efficiency of the support processes with the Technical Efficiency of the launch vehicle itself. There are many process options to support a launch vehicle once the System Performance and System Availability characteristics are defined. The processes used to achieve the vehicle Technical Effectiveness can be very efficient, improving program costs, or very inefficient, requiring much more program expense to achieve high levels of Technical Efficiency. This System Effectiveness measures couples the system characteristics of the launch vehicle with the efficiency of the supporting processes defined by Process Efficiency.

2.5. Total Ownership Cost (TOC)

Total Ownership Cost (TOC) is the measure of the total program cost to manufacture, assemble, launch, and sustain the launch vehicle program. TOC considers all aspects of the launch vehicle costs including development costs, vehicle production costs, annual sustaining engineering costs, and operations costs.

2.6. Affordable Operational Effectiveness

Affordable Operational Effectiveness is the ultimate goal of any launch vehicle program. This measure indicates how efficiently the launch vehicle achieves the intended outcomes of the launch vehicle development and operations. This provides an integrated assessment of TOC, Process Efficiency, and Technical Effectiveness into a visible indicator of development and operations planning and execution success.

3. Launch Vehicle Block Development

The DoD approach incorporates concepts of evolutionary acquisition. Two options are defined to acquire capabilities as they are matured due to funding profiles or technology readiness. These are Incremental or Block Development, and Spiral Development. From a launch vehicle development stand point, the Block Development is the most practical. In Block Development a basic vehicle is fielded. Subsequent blocks then add capabilities in terms of stages, new engines, solid rocket motors, fairing sizes, and payload accommodations. These blocks allow the capabilities of the vehicle to grow to meet new customer needs as the customers become ready for the launch capability. They allow for initial capabilities to support near term customers with phasing of development funding to incrementally improve the launch vehicle capabilities (i.e., mass to orbit, payload classes supported, crew capsule support). Note, that the blocks provide a family of vehicle from which tailored support can be provided to a variety of mission needs. This provides a more affordable approach to launch vehicle operational effectiveness. Figure 7 provides a basic example of block development.

Spiral development allows more flexibility in the final capability of the system capabilities. Spiral is very appropriate for the development of planetary exploration missions and infrastructure or for new and undeveloped propulsion capabilities. For chemical launch vehicles, however, the physics define very clearly the options available and the block development approach is the most directly applicable.

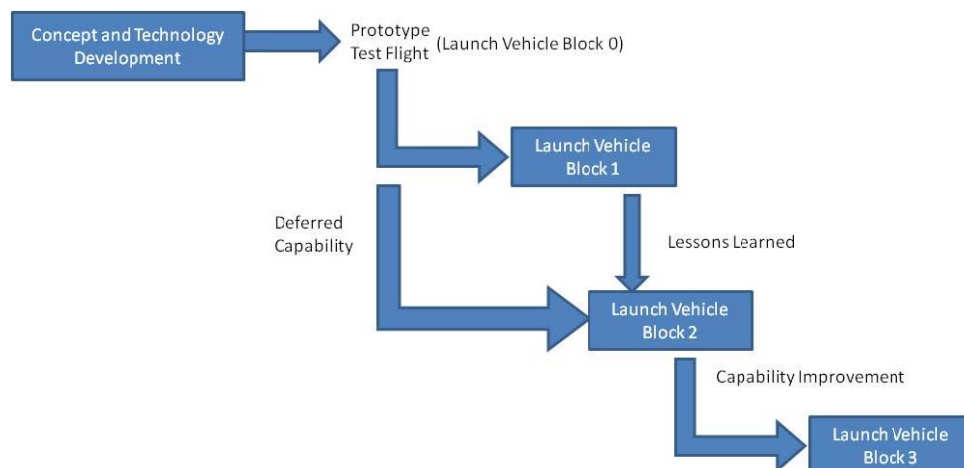


Figure 7: Launch Vehicle Block Development

4. Application of the SOE Model in the Launch Vehicle Life Cycle

In applying the SOE framework to a launch vehicle, an understanding of the life cycle phases of the launch vehicle definition, development, and operations is essential. The mapping of the DoD life cycle phases originally used in the SOE model development and the NASA life cycle phases are illustrated in Figure 8. The DoD life cycle model has three main phases which map well with the NASA model. The sub phases, though, are mapped differently.

DoD typically has a single prime contract that is implemented, so using the SOE model is a straight forward approach. The SOE model becomes multi-dimensional for implementation on programs with multiple contract approaches.

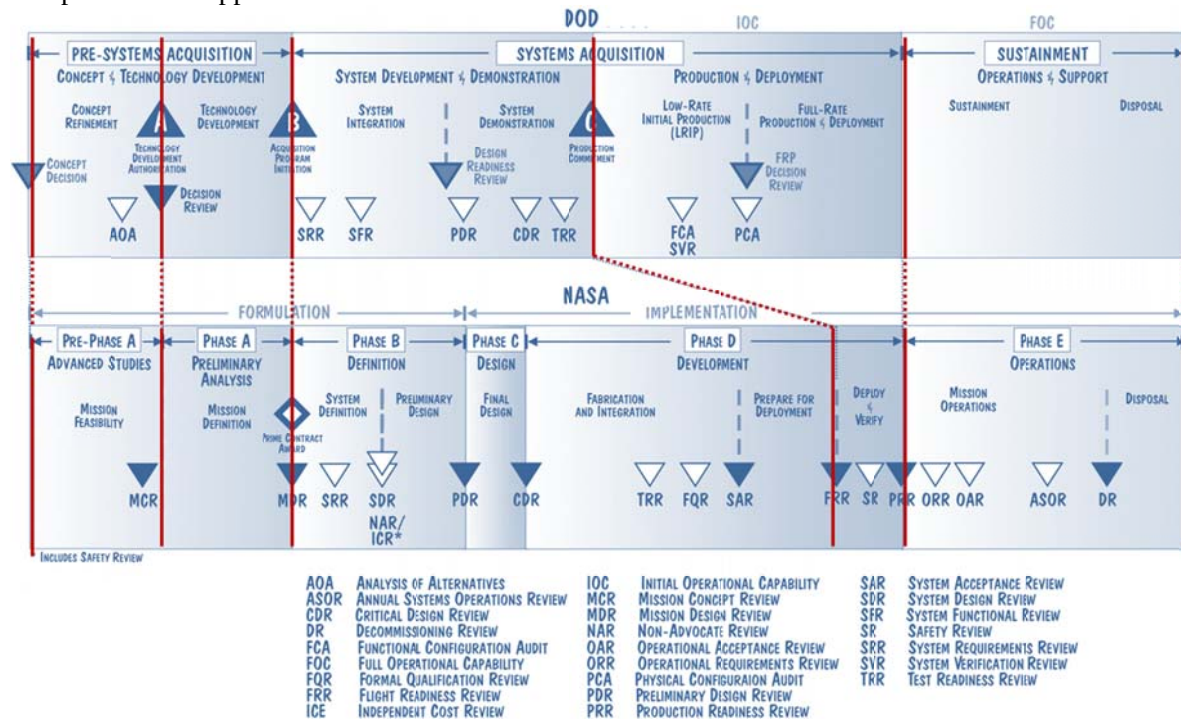


Figure 8: Mapping of DoD Life Cycle Phases to NASA Life Cycle Project Phases

4.1. NASA Pre-systems Acquisition (Pre-Phase A, Phases A, B)

Pre-systems Acquisition encompasses early concept studies (Pre-Phase A), Concept and Technology Development (Phase A), and Preliminary Design (Phase B). During this phase the mission to be supported by the launch vehicle is defined as well as the concept for design of the launch vehicle. This is captured in the Concept of Operations. Understanding the mission context and its relationship to the vehicle concept is critical to designing an effective launch vehicle. Technology starts in Pre-Phase A and continues into Phase A. In general, critical technologies for development of the launch vehicle, in particular high risk technologies, need to be completed before the System Readiness Review (SRR) where the launch vehicle requirements are approved for start of design activities. This phase also includes the preliminary design of the launch vehicle culminating in the PDR. All technologies must be ready to support implementation by PDR. During this pre-systems acquisition phase, the mission context and launch vehicle concepts must be well understood including the operations and supportability requirements. These requirements are essential to cost effective operations during the Operations Phase.

During this phase, 80% of the vehicle production and operations costs are established in terms of the operations and support capabilities supported by the vehicle design. The launch vehicle concept is captured in the Concept of Operations Document and defines the missions and customers to be supported, flight rates, launch site location and environment, system effectiveness, launch vehicle life cycle, and launch vehicle program life cycle. For an expendable vehicle, the launch vehicle life cycle is the time from start of manufacture through mission completion. The program life cycle is from the start of concept definition through program decommissioning (Phase F). In conjunction with the vehicle concept, the launch vehicle support and maintenance concepts are defined which includes launch reliability, expected maintenance rates (which determine processing and launch time lines and maintenance access needs), and obsolescence expectations over the program life cycle.

Technology development is a key aspect of Pre-Phase A and Phase A. This phase involves the maturation of new capabilities necessary to achieve the launch vehicle concepts for capabilities, production and operations, and affordability. Technology demonstrations include demonstration of key supportability concepts. This is particularly important in early launch vehicle test flights. Demonstrations may also be conducted on related vehicle such earlier variants in the launch vehicle family. Key tests during early development activities should be included as part of the System Development Plan (SDP).

The launch vehicle logistics and support concepts are captured in the Integrated Logistics Support Plan (ILSP). This defines the key driving philosophies to accomplish the affordability and sustainment goals during the Production and Operations phase (Phase E). The ILSP addresses the logistics footprint (on-site maintenance, depot maintenance, sparing policy); line replaceable unit (LRU) definition; personnel skills, training, and certification; supply chain management (SCM); and supportability risks. Production and Operation metrics should be captured in the programs technical metrics. In addition, a Failure Management Plan addresses response to processing, launch, and flight failures. A Rough Order of Magnitude (ROM) TOC is completed to define major cost drivers in vehicle capabilities and support plans.

The program risks at this point should consider not only development risks but also the production and operation risks against the launch vehicle operational uses and missions. The output of this phase results in the System Requirements Review (SRR) where the launch vehicle requirements or specifications are base lined.

4.2. NASA Systems Acquisition (Phases C, D)

Systems Acquisition encompasses Final Design and Fabrication (Phase C) along with Vehicle Assembly, Integration & Test, and Launch Operations (Phase D). This phase includes the final design activities of the launch vehicle, verification and validation of the design. In addition, assembly, integration, test and launch operations of the first flight vehicle are conducted in this phase. Depending on the program, more than one test flight may be involved in this phase.

The launch vehicle is designed and developed during this phase. Various production and operation phase capabilities are also defined and put in place. Manufacturing plans are developed with a focus on manufacturing risk reduction. The design incorporates producibility

through manufacturing requirements. Design of operational flight information, temporary monitoring measurements, engineering flight information (post flight analysis and catastrophic flight reconstruction data), vehicle diagnostics, and flight prognostic data are conducted. Verification and validation approaches include operations and logistics and supportability capabilities. Flight test plans incorporate logistics and supportability demonstration objectives.

Operations control teams and centers, and operational communications are developed.

Failure Modes and Effects Analysis (FMEA), Fault Trees, Probabilistic Risk Assessments (PRA), reliability allocations are all conducted during this phase. These critical assessments provide key information for maintenance planning, crew abort conditions, and contingency time lines.

The ILSP establishes the complete logistics footprint and approach, personnel and certification requirements, and data capture and access. Key logistics and support characteristics addressed by the design include launch availability, launch and mission reliability, maintainability (maintenance down time). These characteristics drive the processing and launch countdown time lines. Design assessments are conducted in conjunction with each major design review considering ability to accommodate technology refresh, obsolescence upgrades, SCM replacements over the program life cycle. Maintenance concepts are defined including on pad maintenance, roll back maintenance, and depot maintenance. Logistics and support data are provided to support various program reviews including major design reviews, Key Decision Points (KDP), cost audits, etc. A Maintenance Task Analysis (MTA) and Level of Report Analysis (LORA) are conducted to determine detailed maintenance procedures, LRUs, and sparing needs.

The DoD model addressed both Reliability Centered Maintenance and Condition Based Maintenance. The applicability of these concepts depends on the vehicle concept. Expendable launch vehicle maintenance is reactive to failure conditions. While some preventative maintenance is defined, most maintenance actions are corrective based on the occurrence of a failure condition. Since the life cycle of the vehicle is predominantly during the assembly phase, the failures are not expected due to operational cycles or use. Thus, neither RCM nor CBM apply well. For re-useable launch vehicles, however, RCM and CBM apply as described in the DoD model. These concepts can be applied after each flight and after a set number of flights through the life of the vehicle (which may encompass the life of the program).

TOC estimates are refined from the ROM level to specific Production and Operations cost requirements to be met by manufacturing, transportation, assembly, test, launch, flight operations, and post flight analysis. Affordability throughout the vehicle life cycle must purposefully and explicitly managed during the design and development phase.

4.3. NASA Production and Operations (Phase E)

Production and Operations Activities (Phase E) for a launch vehicle involves the manufacture, assembly, integration, test, and launch operation for the operational missions supported. For a launch vehicle this period is generally decades in length which must be considered in the

supportability assessments conducted early in the vehicle definition and design phases (Phases A, B, C).

The key concepts for launch vehicle application right sizing of the production base. These concepts are categorized as Low Rate Initial Production (LRIP) and Full Rate Production (FRP). For a launch vehicle, production of early blocks, which may involve a subset of customer uses and missions, can be considered LRIP. Basic production capabilities are exercised, but full production capacity is not in place. Expansion to include the full rate production must be in place while the tooling and potential facility costs are deferred until the launch vehicle customers are available/ready to support higher production rates. Early demonstration missions may be more economically supported with LRIP.

FRP is achieved when the full set of missions and customer needs can be accommodated by the production capacity. This capacity must consider the average and peak flows. High launch rate periods may be accommodated through a variety of techniques including temporary storage of stages or vehicles, multiple vehicle processing lines at the launch site, and multiple shift work. The FRP capacity must also consider low flow rates. If the peak rate is used for sizing the production base, then long periods of over production could unintentionally be realized driving up costs to the launch vehicle providers and customers. Average production rates with some surge capacity are generally better than peak rate sizing.

These concepts affect logistics planning drastically. The logistics and support capabilities must be expandable to cope with the increase from LRIP to FRP. Logistics and support must also be able to affordably support surge capacities once FRP is realized.

In addition to production, operations must be planned efficiently. Launch and flight operations are generally more efficiently handled as a consolidated team rather than separate teams. The skills to support launch operations are the same as flight operations with the exception of the launch site systems.

A key aspect to managing P&O phase costs is to conduct regular program Operational Assessments. These assessment cycles should be set based on funding cycles from stakeholders and customers. Major planned block upgrades should be associated with a program assessment of logistics, supportability, and operations efficiency at the initial of block developments and as the block upgrade is brought into operational use.

4.4. NASA Decommissioning (Phase F)

Program Close out (Phase F) involves the orderly shutdown of the program including disposition of remaining assets, transition of manufacturing facilities, and the capture and retention of lessons learned and key technical data for historical purposes and potential application on future launch vehicle developments. These plans must be put in place with sufficient time to affect and orderly shutdown of the program. This is a long lead activity that needs to be planned at least 5 years before the decommissioning date in order to properly disposition and transfer assets.

5. Summary

System Operational Effectiveness provides a strong framework from which to measure and manage the effectiveness of a launch vehicle performance, availability, and process efficiency. This framework maps well to the NASA launch vehicle development and operations concepts. SOE provides the framework in which technical performance metrics can be defined, integrated, and related to provide a more complete understanding of the vehicle capabilities and support systems. In order to achieve affordable operational effectiveness, the launch vehicle must be designed for support and the support systems must support the design. This relationship is essential as no processes can compensate for a vehicle not designed for support. As the launch vehicle moves from definition through design, the SOE measures and focus change with the design maturity. The focus shifts from design for support as these capabilities are designed in to the vehicle to support definition for the design. This yields a launch vehicle with matching support capabilities ready for mission support beginning with the first launch. As the program moves to the P&O phase, the production base must be right sized to the anticipated mission flow rate. The concepts of LRIP and FRP provide a basis from which to transition from low early mission launch rates to higher mission rates as the program matures and the customer base expands. The production base in this case must be able to accommodate surge capacities to keep from over sizing the production base. Logistics and support capabilities must be scalable with the production capacities as the program moves from LRIP to FRP.

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BIOGRAPHY

Michael D. Watson is the National Aeronautics and Space Administration (NASA) Space Launch System (SLS) Lead Discipline Engineer for Operations Engineering. He started his career with NASA developing International Space Station (ISS) Payload Training Complex and the ISS Payload Data Services System (PDSS). He also worked to develop remote operations support capabilities for the Spacelab Program installing Remote Operations Centers and services in the United States, Europe, and Japan. He subsequently served as Chief of the Optics Branch responsible for the fabrication of large x-ray telescope mirrors, diffractive optics, telescope systems. He served as Chief of the Integrated Systems Health Management (ISHM) and Sensors Branch and led a NASA team defining Vehicle Management System capabilities for human missions to Mars. His branch work included the definition of ISHM capabilities for the Ares family of launch vehicles. He graduated with a BSEE from the University of Kentucky in 1987 and obtained his MSE in Electrical and Computer Engineering (1996) and Ph.D. in Electrical and Computer Engineering (2005) from the University of Alabama in Huntsville.

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